Distribution System Analysis Tools for Solar Integration

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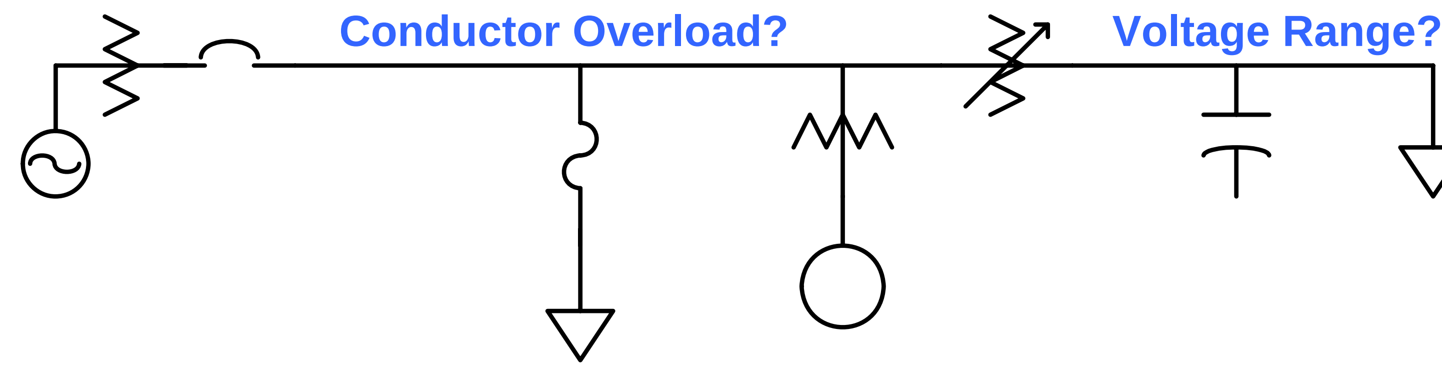
UWIG Utility Wind Integration Group Distributed Wind Impacts Project

Objectives

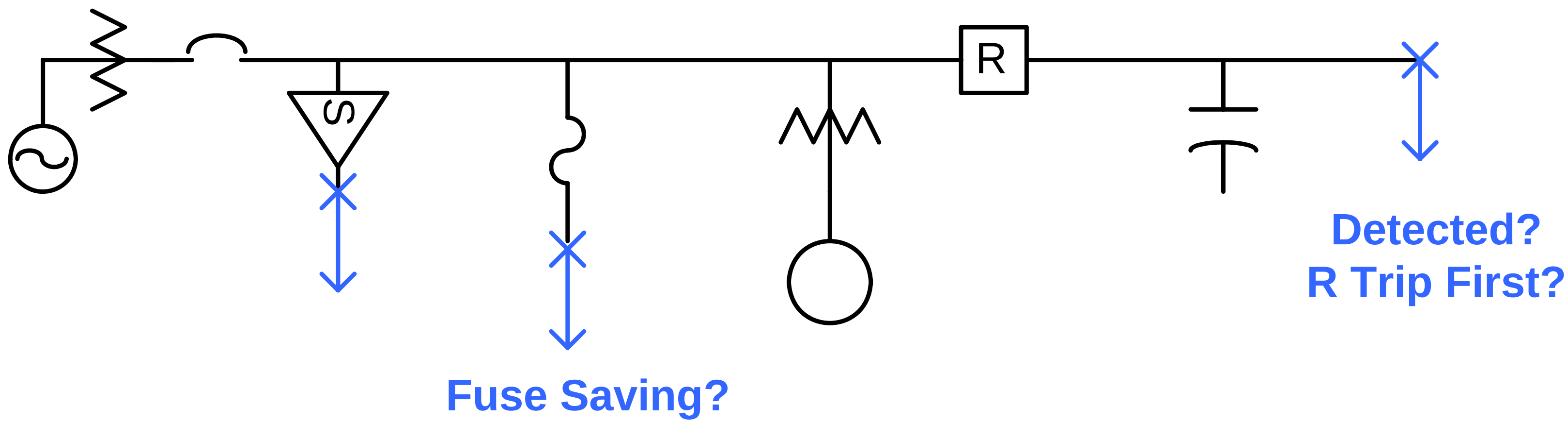
- Technically sound method of aggregating small size PV on distribution systems
- Efficient tool for PV impact studies
- Optimal control strategies for distributed PV
- Promote and leverage the development of models and tools

Distribution Software Tasks

- Current Flow and Voltage Drop



- Overcurrent Protective Device Coordination



Status of Distribution Software

- Tools with DG-specific functions
  - CYMDIST
  - OpenDSS
- Others have conventional SG/IG models
- CAPE and ASPEN have current-limited sources
  - ASPEN DistriView might not have this
- What happens with “many” PV sources; i.e., strongly looped systems?
- Keep pushing software vendors!

UWIG Screening Tool Inputs

- WTG Library
- Estimate Z

Select Project: Pike County*		New / Delete
Project Name	Pike County*	Calc / Update
Turbine (WTG) Inputs:		
Turbine Type	Vestas NM82 / 1650	☐ Unlisted Type
Size	1652.00	kW
Generator / Interface	◉ Induction ○ Wound Rotor ○ DFIG ○ Converter	
Per-unit Fault Current	6.00	
Operating Power Factor	1.00	
Number of Turbines	1	
Average Wind Speed at the Site	5.50	m/s
Feeder Inputs:		
Substation Transformer	5.00	MVA
	7.19	% Z
Feeder Primary Voltage	12.47	kV
Line Conductor Type	Unbalanced 336 ACSR	
WTG Distance from Sub	29.04	kft
Peak Load	2.40	MW
Capacitor Banks	0.00	kVAR
Regulator Distance from Sub	0.00	kft

UWIG Screening Tool Outputs

FERC Fast-Track Acceptance (not in all jurisdictions)
- Design is certified (UL 1741)
- Project size ≤ 2 MW
- Size ≤ 15% of Segment Load
- Contribute ≤ 10% Utility Fault Current
- All Utility Devices ≤ 87.5% Fault Rating
- (capacity factor for info only)

Voltage Change ≤ 5%

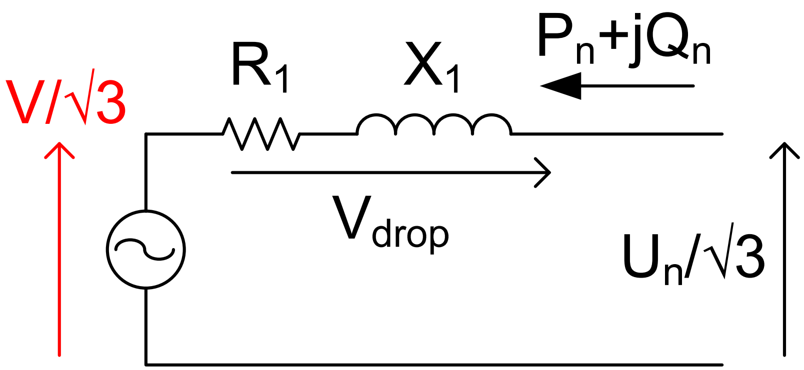
Flicker Planning Levels (IEEE Std. 1453)
- Continuous, $P_{ST} \leq 0.9$
- Switching, $P_{ST} \leq 0.9$ and $P_{LT} \leq 0.7$

Screening Outputs:		
WTG Portion of Peak Load	68.83	%
WTG Fault Contribution	0.35	kA
WTG Portion of System Fault	29.24	%
FERC Fast-track?	Study Required due to Load Level, Fault Level	
Estimated Capacity Factor	22.5	%
Flicker Outputs:		
System Apparent Power	26.08	MVA
System Impedance Angle	73.60	Degrees
On/Off Voltage Change	1.97	%
Continuous P_{ST}	0.14	
Switching P_{ST}	0.71	
Switching P_{LT}	0.50	
Feeder Simulator...	Economic Analysis...	

Shortcut to a Feeder Simulator Model

Screening Tool Background

Estimated % Voltage Change:



$$V_{drop} = \frac{100}{U_n^2}(R_1 + jX_1)(P_n - jQ_n)$$

$$\frac{dV}{U_n} = \sqrt{(100 + \mathrm{Re}V_{drop})^2 + (\mathrm{Im}V_{drop})^2} - 100$$

(R, X in ohms, S_n in MVA, U_n in kV)

Flicker Estimates:

$$P_{st-c} = C_f(\phi, v)\frac{S_n}{S_k}$$

$$P_{st-k} = 15\sqrt[3.2]{N_{10}}K_f\frac{S_n}{S_k}$$

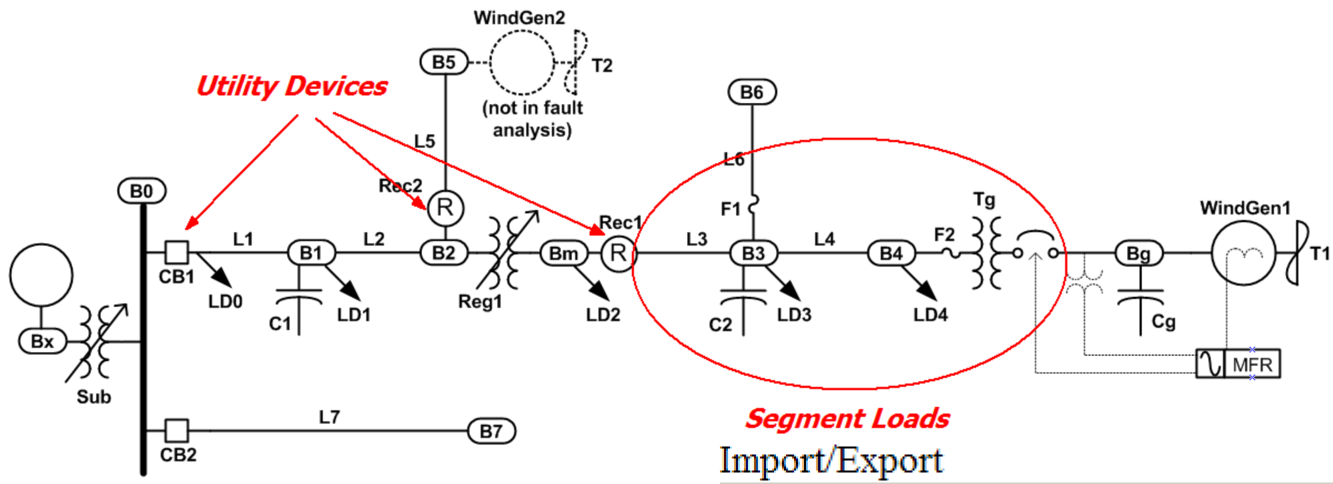
$$P_{lt-k} = 6.9\sqrt[3.2]{N_{120}}K_f\frac{S_n}{S_k}$$

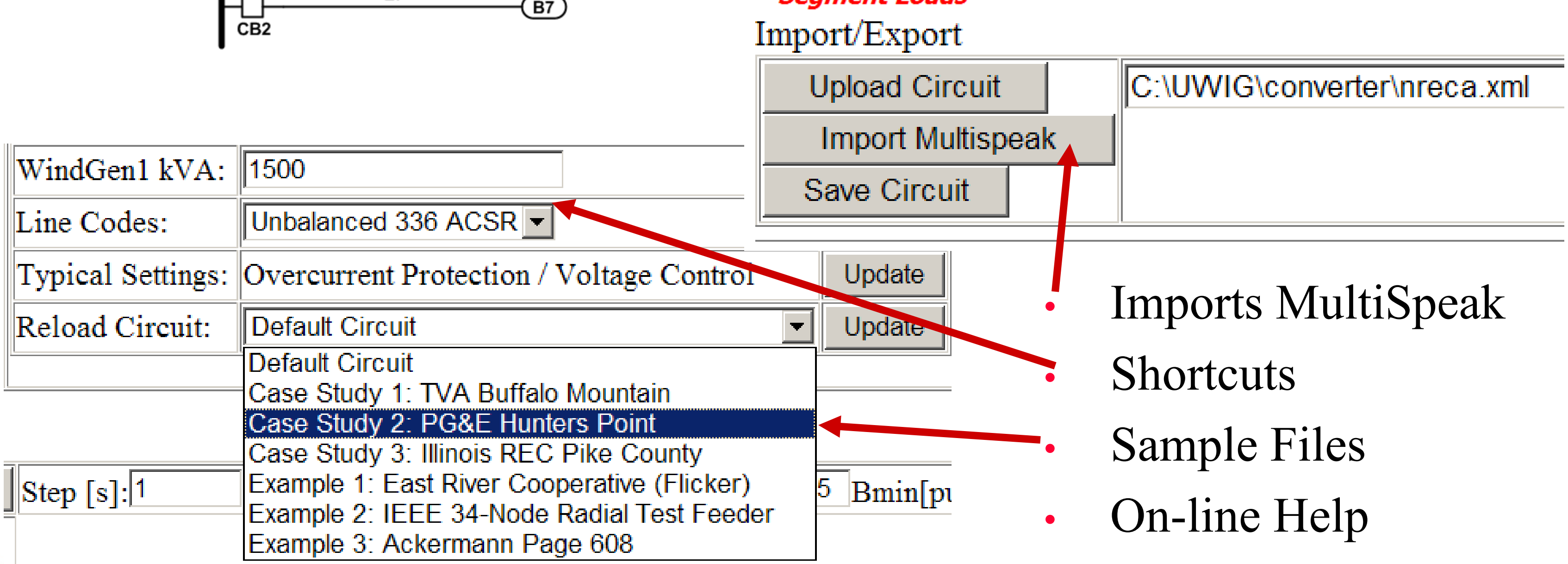
Multiple WTG Weighting:

$$P_c = \sqrt{\sum_i P_{c-i}^2}$$

$$P_k = \sqrt[3.2]{\sum_i P_{k-i}^{3.2}}$$

UWIG Feeder Simulator



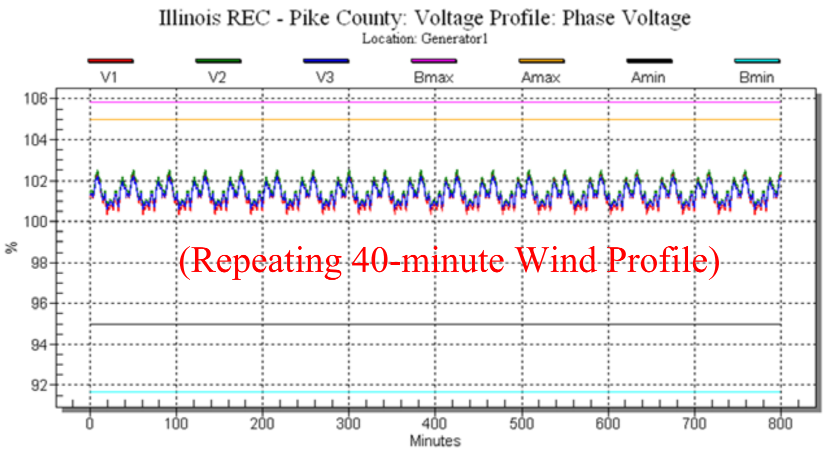


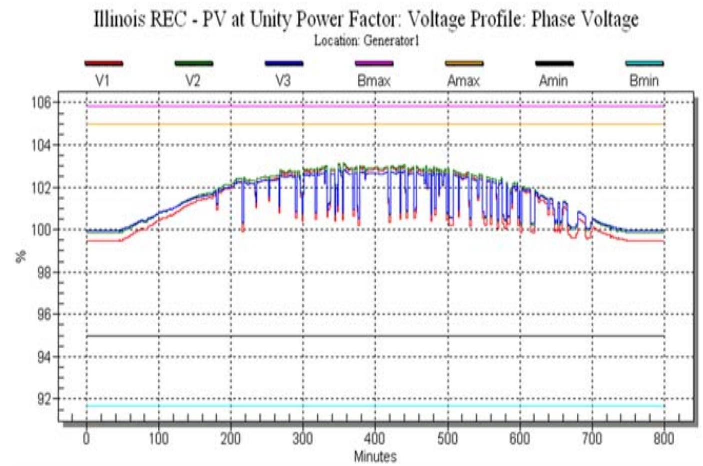
- Imports MultiSpeak
- Shortcuts
- Sample Files
- On-line Help

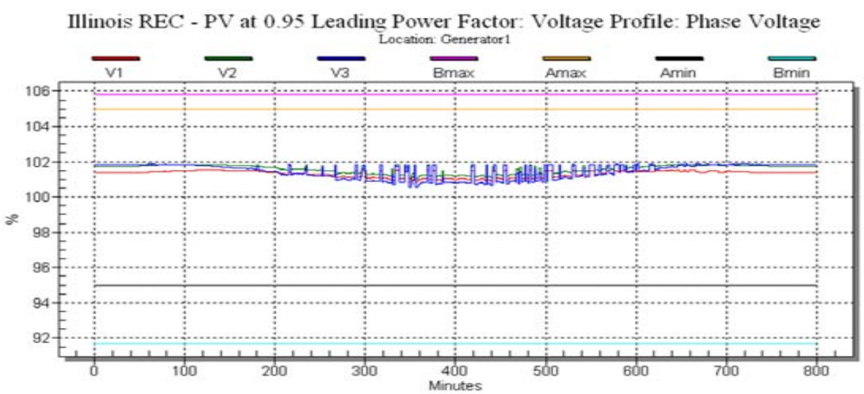
Feeder Simulator Features

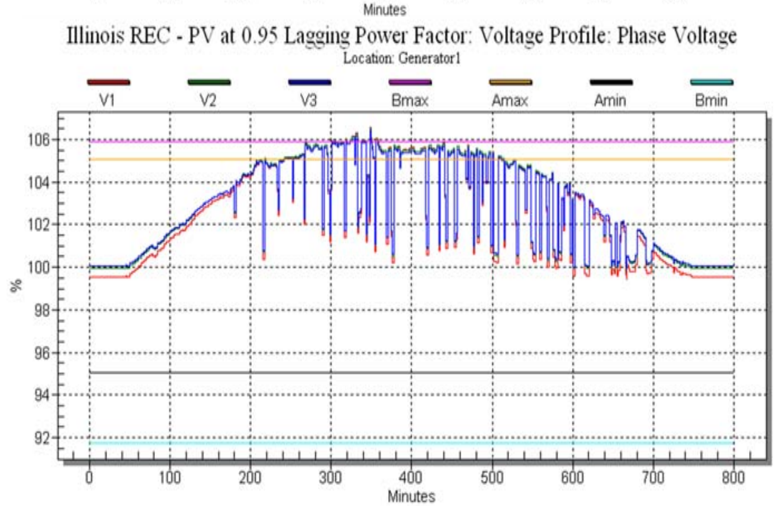
- Voltage fluctuations with variable power output, capacitor switching, and tap changing
- Faults and overcurrent protection with DG
- Temporary overvoltage during backfeed
- Two connection points for DG
- MultiSpeak Import
- Streamlined Model Creation from the Screener
- OpenDSS Export

Sample Voltage Fluctuations



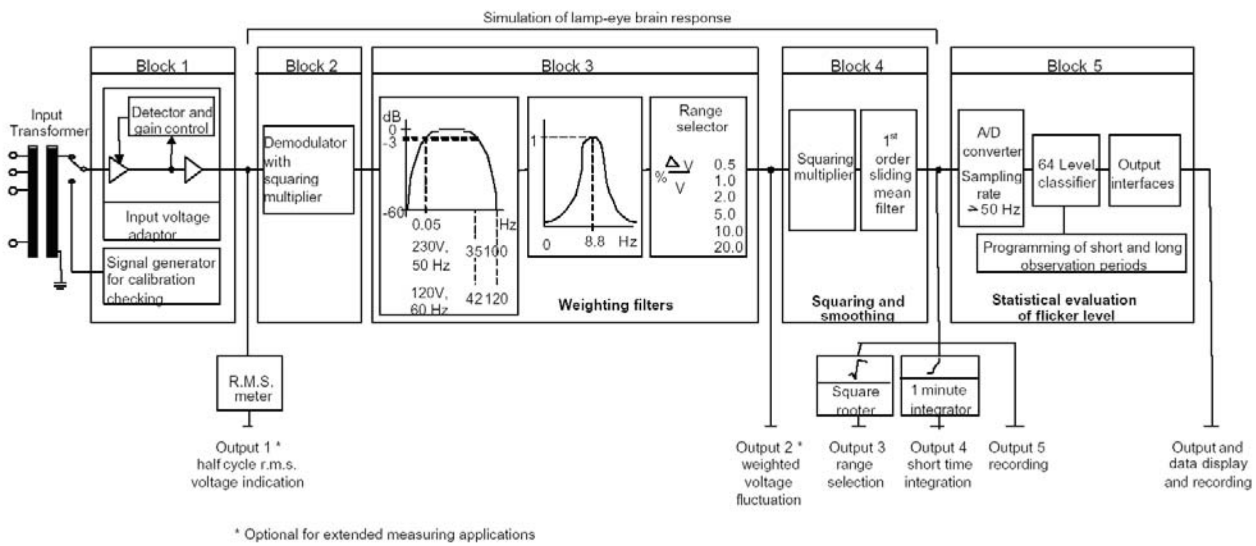






PV Profiles at Different Power Factor Show the Potential for Voltage Control

IEEE Std. 1453 Flicker “Meter”



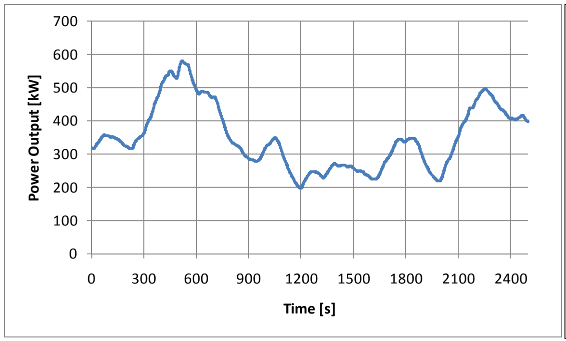
- Implement this in software
- Any voltage fluctuation produces a single output

Flicker Severity Level	Compatibility Level	Planning - MV	Planning – HV & EHV
P_{st} [10-minute]	1.0	0.9	0.8
P_{lt} [120-minute]	1.0	0.7	0.6

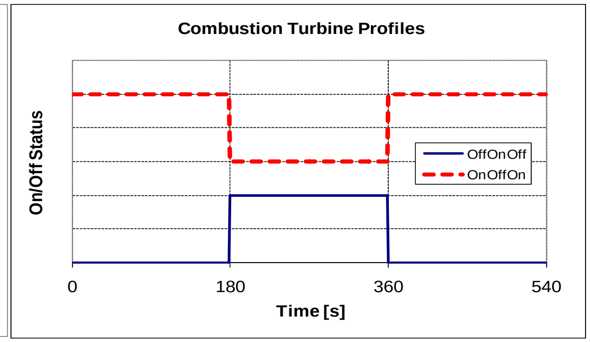
UWIG 4-Day Study Process

- Screening Evaluation ➔ Feeder Simulator Model
- Estimate Probability of Substation Export
- Feeder-level Analysis
  - Evaluate application vs. IEEE Std. 1547
  - Power variation impact on voltage profile and control
  - Review regulator and capacitor control settings
  - Systematic fault analysis with and without DG
  - Temporary overvoltage analysis
  - Review and specify relay settings
- Letter Report

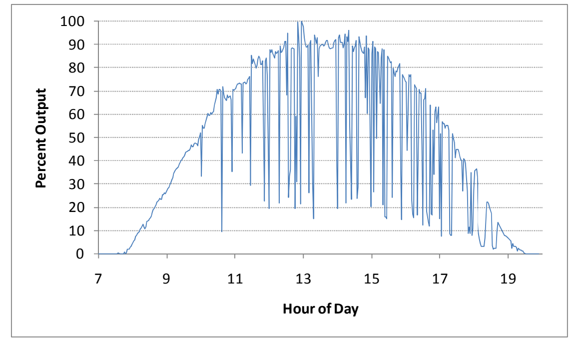
Existing Power Profiles



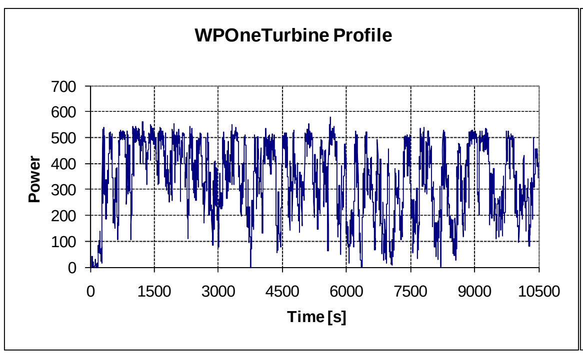
40-minute Wind

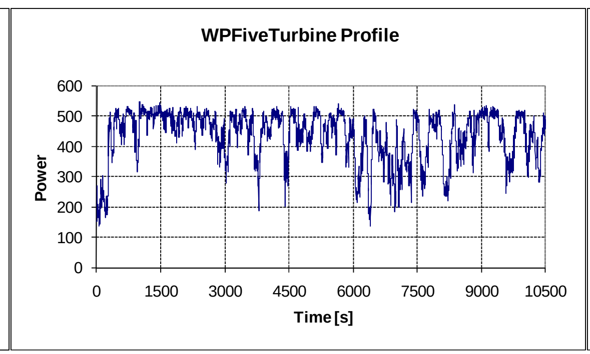


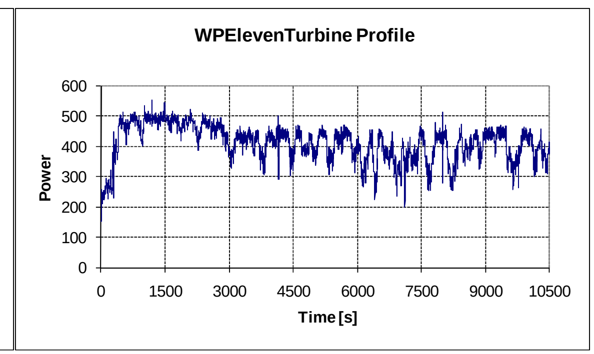
Conventional Generator



Daily PV (50 kW Unit)







3-Hour Wind with Different Numbers of Turbines

How to Aggregate Multiple DG?

- Distribution tools need time steps down to 1 second for voltage control simulations
- Markov chains?
  - Reproduce probability density, but not autocorrelation
  - This problem is worse at shorter time steps

From Brokish & Kirtley, "Pitfalls of Modeling Wind Power Using Markov Chains", IEEE PSCE 09.

Also discussed in Y. Wan's NREL reports.

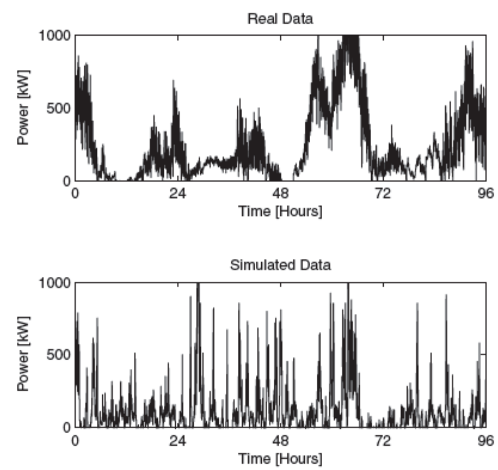


Fig. 1. Markov chains at small time steps clearly differ from the original data

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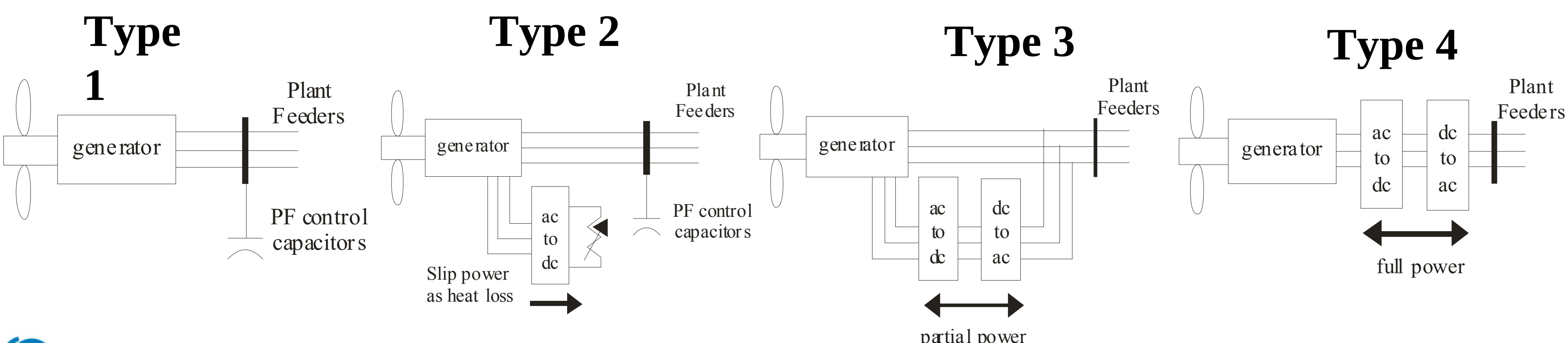
Other Aggregation Approaches

- All these are suitable for software implementation
  - Autoregressive Moving Average (ARMA)
  - Wavelets
  - Artificial Neural Networks and other Heuristics
- Allow users to choose or upload a single-unit power profile
- Reduce the standard deviation around the scaled power profile for multiple units (NREL data for wind, need some data for PV)

Wind Turbine Generator Models

- General wind turbine model types (per WECC, IEEE, Cigre)
  - Type 1 – conventional induction generator
  - Type 2 – wound rotor induction generator, variable rotor resistance
  - Type 3 – doubly-fed induction generator
  - Type 4 – full converter interface, similar to PV
- We need reasonable average short-circuit contributions to check overcurrent device coordination on the feeder



Doubly-Fed Induction Machine

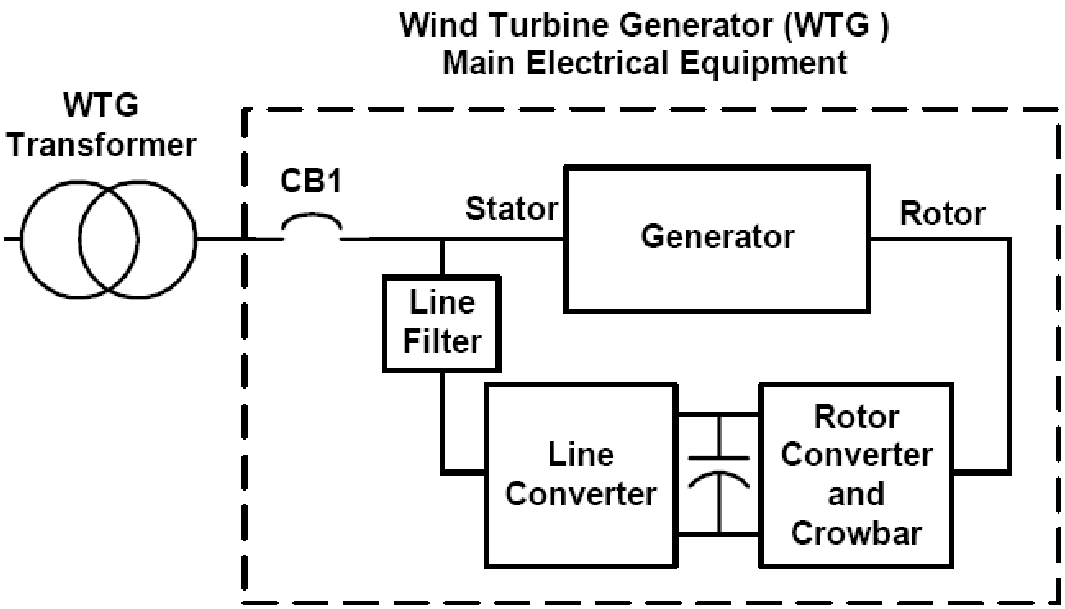
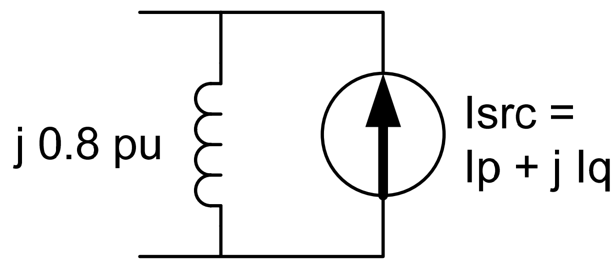


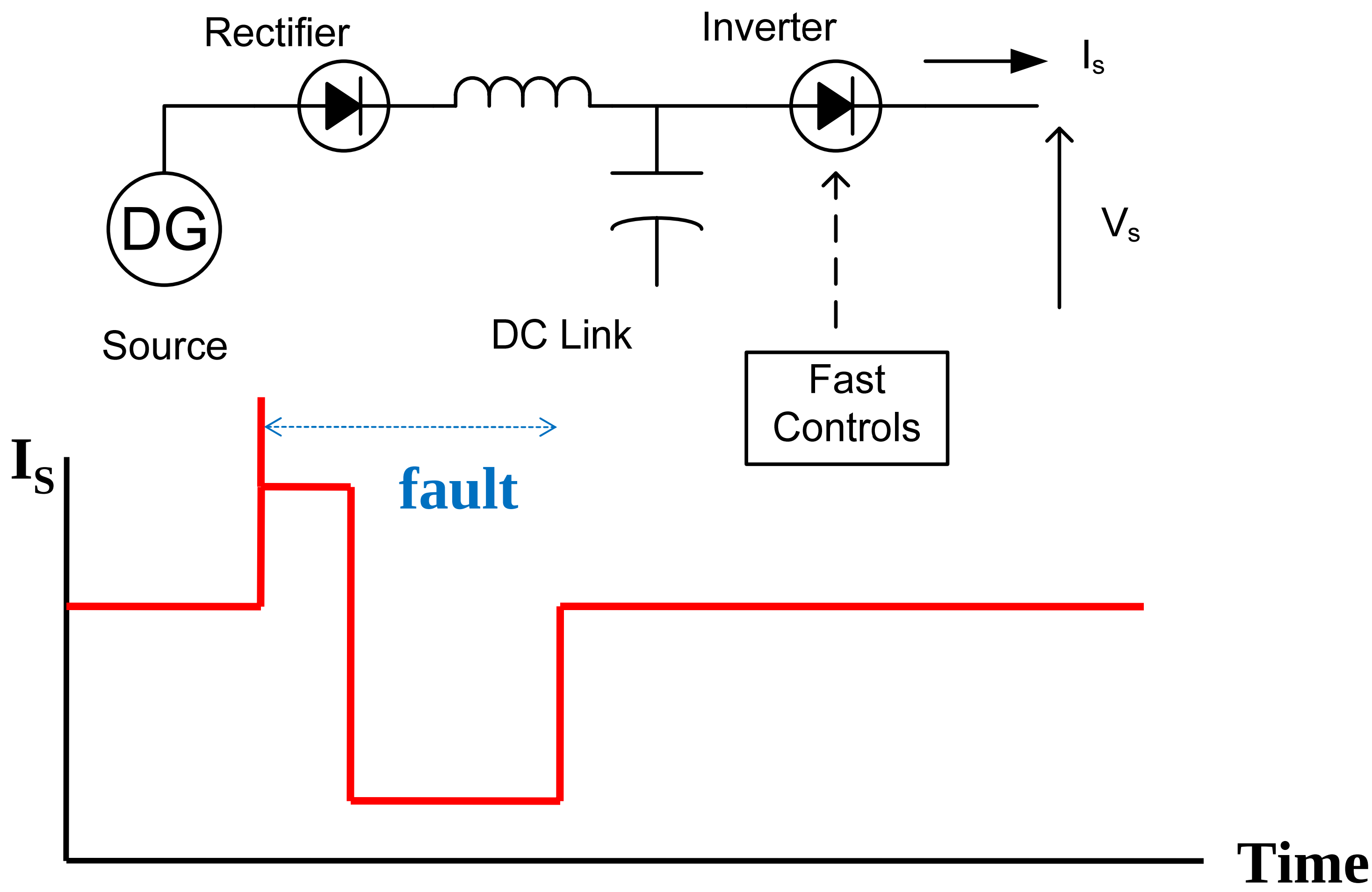
Figure 2.1 Overview – GE 1.5MW WTG



Without Rotor Crowbar

With Rotor Crowbar, looks like an Induction Machine

Current-Limited DR



WTG Models for Distribution

Turbine Type	Power Flow	Short Circuit
1 – Squirrel Cage	Constant Q or PF Include Capacitor Switching Steps	Locked Rotor (about 6 * Rated Current) Xdp ≈ 0.17
2 – Wound Rotor		
3 – Doubly Fed	Constant Q or PF Inherently No Cap Not a PV bus per IEEE Std. 1547	Limited by Converter Xdp ≈ 0.50-0.90
4 – Power Electronic		

19

What is Needed for PV?

- Aggregate models of variability
- Fast-average models of dynamic response to faults
- A common format for vendor-supplied models
- Software tools that:
  - Simulate variability
  - Simulate fault contributions from many PV units

Backup – WTG Types 1 and 2

- Power flow, input scheduled P and Q
  - Given voltages, solve for speed, current, machine Q
  - Add capacitor steps to approximate scheduled Q
- Short circuit
  - I_{qs}, I_{ds}, I_{qr}, I_{dr} already initialized
  - Use "fast average" model for currents

$$p\bar{I}_{qs} = \frac{\bar{V}_{qs} - r_s \bar{I}_{qs} - \bar{\omega}_r L_s \bar{I}_{ds} - \bar{\omega}_r L_m (\bar{I}_{qs} + \bar{I}_{qr})}{L_s}$$

Backup – WTG Types 3 and 4

- Inputs
  - Scheduled P and Q
  - Limits on Ip and Iq
  - Time delay to reset
- Normal power flow solution for a PQ source
- Short-circuit solution
  - Assume a low equivalent impedance
  - Apply separate limits on I_p and I_q, inject the total
- Later, fast-average model for rotor crowbar

Conclusions

- More DR models in commercial software
- Modeling options in commercial software
  - Behavioral (equation-based) is easier for users
  - Standard languages are easier for users
- Vendor-supplied DR models
  - Protecting proprietary information
  - In portable formats
  - Semiconductor, automotive, and other industries already do this